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# Yukawa Corrections to Top Quark Production at the LHC in Two-Higgs-Doublet Models

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ABSTRACT

The $O(\alpha m_t^2/m_W^2)$ Yukawa corrections to top quark pair production by $gg$ fusion at the LHC are calculated in two-higgs-doublet models. We find that the correction to the cross-section can exceed about $-10\%$ for certain parameter values.

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# I. Introduction

Recently, the existance of the top quark is confirmed by the CDF and D0 Collaborations with the mass and production cross-section $m_t = 176 \pm 8(stat) \pm 10(syst)$ GeV $\quad \sigma = 6.8^{+3.6}_{-2.4} pb$, and $m_t = 199^{+19}_{-20}(stat) \pm 22(syst)$ GeV $\quad \sigma = 6.4 \pm 2.2 pb$, respectively [1] . This is a remarkable success of the Standard Model (SM) since this measured mass is close to the central value predicted by the best fit of the SM to the LEP precision electroweak data. There are a number of new and interesting issues related to the top quark, such as the precision measurement of the mass, width and Yukawa couplings through its direct production and subsequent decay at both hadron and $e^+e^-$ colliders. At the future multi-TeV proton colliders such as the CERN Large Hadron Collider (LHC), $t\bar{t}$ production will be enormously larger than the Tevatron rates, and the accuracy with which the top mass can be measured in proton colliders is around 2 GeV[2]. This makes the determination of production cross section at LHC more accurately than at Fermilab Tevatron. Processes related to the top quark (the heaviest fermion so far found) may be sensitive to possible new physics beyond the SM, especially the non-standard Higgs sector, due to the large Yukawa coupling.

The simplest extension of the SM Higgs sector is the two-Higgs-doublet models (2HDM) which can give an enhancement of the Yukawa couplings and may result in a considerable correction to the top quark production cross section. Yukawa correction to the top quark production in general 2HDM and in the minimal supersymmetric model(MSSM) at Fermilab Tevatron has been carried out in Ref. [3], where large corrections are found. Supersymmetric electroweak correction [5] and

QCD correction[6] to top quark production at the Tevatron are also found to be large. At LHC the main production mechanism of top quark is the gluon-gluon fusion process $gg \to t\bar{t}$. The full electroweak corrections to this process as well as $qq \to t\bar{t}$ in the Standard Model have been calculated in Ref. [4]. In this paper we investigate the Yukawa correction to the top quark production by the process $gg \to t\bar{t}$ in a general 2HDM and in the minimal supersymmetric model at LHC. Our calculation of the corrections to the S-matrix elements will be given in Sec.II. In Sec III, we present our numerical results and discussions of the cross-sections in the SM , 2HDM and MSSM .

## II. Calculation of the S-matrix Elements

The tree-level Feynman diagrams and the relevant Yukawa corrections to $gg \to t\bar{t}$ are shown in Fig.1 (u-channel diagrams of Fig.1b and Fig.1d–Fig.1h are not explicitly shown) in which the dashed lines in Fig.1c and Fig.1e–Fig.1h represent $H^0$, $h$, $A$, $G^0$, $H^+$ and $G^+$ ($G^0$ and $G^+$ are, respectively, Goldstone bosons of $Z$ and $W^+$), while those in Fig.1d represent only $H^0$ and $h$. The relavant Feynman rules can be found in Ref.[7].

At tree level, the S-matrix element is composed of three different production channels(s-,t-,u-channel) as follows:

$$
\begin{aligned}
M_0^s &= -ig_s^2 i f_{abc} T_{ji}^c \Gamma^\mu \bar{u}(p_2)\gamma_\mu v(p_1)/\hat{s} && (1)\\
M_0^t &= -ig_s^2 (T^b T^a)_{ji} \epsilon(p_4)^\mu \epsilon(p_3)^\nu \bar{u}(p_2)\gamma_\mu(\not{p}_2 - \not{p}_4 + m_t)\gamma_\nu v(p_1)/(\hat{t} - m_t^2) && (2)\\
M_0^u &= M_0^t(p_3 \leftrightarrow p_4,\ \ T^a \leftrightarrow T^b,\ \ \hat{t} \to \hat{u}), && (3)
\end{aligned}
$$

where $\Gamma^\mu$ is given in the Appendix. Instead of calculating the square of the amplitudes explicitly, we calculate the amplitudes numerically by using the method of Ref. [8]. This method greatly simplifies our calculations.

The $O(\alpha m_t^2/m_W^2)$ Yukawa corrections to $gg \to t\bar{t}$ are shown in Fig.1c–Fig.1h, where Fig.1d alone is gauge invariant and the sum of Fig.1c,Fig.1e–Fig.1h is gauge invariant. In our calculation, we use dimensional regularization to regulate the ultaviolet divergences and adopt the on-mass-shell renormalization scheme.

We only give the explicit results of the s- and t-channel contributions to the total Yukawa correction. The u-channel results can be obtained by the following substitutions:

$$p_3 \leftrightarrow p_4, \quad T^a \leftrightarrow T^b, \quad \hat{t} \leftrightarrow \hat{u}. \tag{4}$$

Fig.1c leads to the s-channel vertex correction $\delta M^{s1}$ :

$$\delta M^{s1} = \frac{\alpha m_t^2}{16\pi m_W^2 s_W^2}(-ig_s^2) i f_{abc} T^c_{ji} \Gamma^\mu \bar{u}(p_2)(f_1^{s1}\gamma_\mu + f_2^{s1} p_{2\mu}) v(p_1)/\hat{s} \tag{5}$$

The s-channel Higgs exchange of Fig.1d gives $\delta M^{s2,t}$:

$$\begin{aligned} \delta M^{s2,t} = & \frac{\alpha m_t^2}{16\pi m_W^2 s_W^2}(-ig_s^2)\frac{\delta_{ab}}{2}\delta_{ji}\sum_{i=H^0,h}\eta_i \frac{1}{\hat{s}-m_i^2+im_i\Gamma_i}\epsilon(p_4)^\mu \epsilon(p_3)^\nu \\ & \bar{u}(p_2)(f_1^{s2} g_{\mu\nu} + f_2^{s2} p_{3\mu} p_{4\nu}) v(p_1) \end{aligned} \tag{6}$$

The top quark self-energy $\delta M^{self,t}$ of Fig.1e is:

$$\begin{aligned} \delta M^{self,t} = & \frac{\alpha m_t^2}{16\pi m_W^2 s_W^2}(-ig_s^2)(T^b T^a)_{ji}\epsilon(p_4)^\mu \epsilon(p_3)^\nu \bar{u}(p_2)\gamma_\mu(\not{p}_2 - \not{p}_4 + m_t) \\ & [f_1^{self,t} + f_2^{self,t}(\not{p}_2 - \not{p}_4)](\not{p}_2 - \not{p}_4 + m_t)\gamma_\nu v(p_1)/(\hat{t} - m_t^2) \end{aligned} \tag{7}$$

$\delta M^{v1,t}$ and $\delta M^{v2,t}$ of the vertex corrections (Fig.1f–Fig.1g) are:

$$\begin{aligned} \delta M^{v1,t} = & \frac{\alpha m_t^2}{16\pi m_W^2 s_W^2}(-ig_s^2)(T^b T^a)_{ji}\epsilon(p_4)^\mu \epsilon(p_3)^\nu \bar{u}(p_2)(f_1^{v1,t}\gamma_\mu + f_2^{v1,t} p_{2\mu} \\ & + f_4^{v1,t}\gamma_\mu \not{p}_4 + f_5^{v1,t} p_{2\mu}\not{p}_4)(\not{p}_2 - \not{p}_4 + m_t)\gamma_\nu v(p_1)/(\hat{t} - m_t^2) \end{aligned} \tag{8}$$

$$\delta M^{v2,t} = \frac{\alpha m_t^2}{16\pi m_W^2 s_W^2}(-ig_s^2)(T^bT^a)_{ji}\epsilon(p_4)^\mu\epsilon(p_3)^\nu\bar{u}(p_2)\gamma_\mu(\not{p}_2 - \not{p}_4 + m_t)$$
$$(f_1^{v2,t}\gamma_\nu + f_2^{v2,t}p_{1\nu} + f_4^{v2,t}\not{p}_3\gamma_\nu + f_5^{v2,t}\not{p}_3 p_{1\nu})v(p_1)/(\hat{t} - m_t^2) \quad (9)$$

$\delta M^{box,t}$ of the box diagram (Fig.1h) is:

$$\begin{aligned}\delta M^{box,t} = & \frac{\alpha m_t^2}{16\pi m_W^2 s_W^2}(-ig_s^2)(T^bT^a)_{ji}\epsilon(p_4)^\mu\epsilon(p_3)^\nu\bar{u}(p_2)[f_1^{b,t}\gamma_\nu\gamma_\mu + f_2^{b,t}\gamma_\mu\gamma_\nu \\ & +f_3^{b,t}p_{1\nu}\gamma_\mu + f_4^{b,t}p_{1\mu}\gamma_\nu + f_5^{b,t}p_{2\nu}\gamma_\mu + f_6^{b,t}p_{2\mu}\gamma_\nu + f_7^{b,t}p_{1\mu}p_{1\nu} \\ & +f_8^{b,t}p_{1\mu}p_{2\nu} + f_9^{b,t}p_{2\mu}p_{1\nu} + f_{10}^{b,t}p_{2\mu}p_{2\nu} + \not{p}_4(f_{11}^{b,t}\gamma_\nu\gamma_\mu \\ & +f_{12}^{b,t}\gamma_\mu\gamma_\nu + f_{13}^{b,t}p_{1\nu}\gamma_\mu + f_{14}^{b,t}p_{1\mu}\gamma_\nu + f_{15}^{b,t}p_{2\nu}\gamma_\mu + f_{16}^{b,t}p_{2\mu}\gamma_\nu \\ & +f_{17}^{b,t}p_{1\mu}p_{1\nu} + f_{18}^{b,t}p_{1\mu}p_{2\nu} + f_{19}^{b,t}p_{2\mu}p_{1\nu} + f_{20}^{b,t}p_{2\mu}p_{2\nu})]v(p_1)\end{aligned} \quad (10)$$

The following parameters are used in our calculation:

$$\begin{aligned}&\sqrt{s} = 14TeV, \quad m_t = 176GeV, \\ &\text{MRS parton distribution set A}'[9], \quad Q^2 = \hat{s}, \\ &|\eta| < 2.5, \quad p_T > 20\ GeV.\end{aligned} \quad (11)$$

The $\eta$ and $p_T$ cuts are used in order to avoid the singularities in the calculation of form factors and increase the relative corrections.

# III. Numerical Results and Discussions

In our calculation, we checked our program with gauge invariance and it is accurate to $10^{-10}$. For comparison, we first give the results of the SM in Fig.2. We see that the SM results are always negative and do not exceed $-1.5\%$. The shape of the curve is like that of Ref. [4]. In Fig.3 and Fig.4 we present the results of the general 2HDM and the MSSM with a small $\beta = 0.25$ as in Ref. [3]. In the general 2HDM, the correction can be positive or negative depending on the value of $m_H = m_h$. The positive correction can reach about 5% and the negative about

$-7\%$ which may be potentially observable experimentally. The MSSM results are all negative and can reach as large as $-10\%$ for $m_{H^\pm} < 400$ GeV. The results of the MSSM with $\tan\beta = 1$ are given in Fig. 5. The corrections never exceed $-2\%$. Therefore, if $\tan\beta$ cannot be small as may be in the case of the MSSM, the Yukawa corrections will be too small to be observable. Although there is a factor $\frac{m_b^2}{m_t^2}\tan^2\beta$ in $\eta_{H^+}$, the results vary insensitively with $\beta$ in the large $\tan\beta$ region as shown in Fig.6 for the MSSM with $\tan\beta = 70$. This conclusion is also valid for a general 2HDM.

Therefore, we come to the conclusion that for small $\beta$, in the general 2HDM and the MSSM, the Yukawa corrections to $gg \to t\bar{t}$ at LHC can exceed about $-10\%$ which may be potentially observable. For larger $\tan\beta = 1$, the Yukawa corrections in the general 2HDM and the MSSM will not be observable.

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# Appendix

We give here the form factors for the matrix element appeared in the text. They are written in terms of the conventional one-, two-, three- and four-point scalar loop integrals defined in Ref.[10]. We set $M_Z$ and $M_W$ to zero in the numerical calculation as in Ref. [3].

$$
\begin{aligned}
f_1^{s1} &= -\sum_{i=H^0,h} \eta_i[\frac{1}{2} - 2C_{24} - Z_i^v + m_t^2(4C_0 - C_{21}) \\
&\quad -k^2(C_{22} - c_{23})](-p_2, k, m_i, m_t, m_t) \\
&\quad -\sum_{i=A,Z} \eta_i[\frac{1}{2} - 2C_{24} - Z_i^v - m_t^2 C_{21} \\
&\quad -k^2(C_{22} - C_{23})](-p_2, k, m_i, m_t, m_t) \\
&\quad -\sum_{i=H^+,W^+} \eta_i[\frac{1}{2} - 2C_{24} - Z_i^v + m_t^2(C_0 - C_{21}) \\
&\quad -k^2(C_{22} - C_{23})](-p_2, k, m_i, m_b, m_b) \\
f_2^{s1} &= -\sum_{i=H^0,h} \eta_i[2m_t(2C_{11} + C_{21})](-p_2, k, m_i, m_t, m_t) \\
&\quad -\sum_{i=A,Z} \eta_i[2m_t C_{21}](-p_2, k, m_i, m_t, m_t) \\
&\quad -\sum_{i=H^+,W^+} \eta_i[2m_t(C_{11} + C_{21})](-p_2, k, m_i, m_b, m_b) \\
f_1^{s2,t} &= 4m_t[\frac{1}{2} + m_t^2 C_0 - p_3 \cdot p_4(2C_{22} - 2C_{23} + C_0)](p_4, -k, m_t, m_t, m_t) \\
f_2^{s2,t} &= 4m_t[C_0 + 4(C_{22} - C_{23})](p_4, -k, m_t, m_t, m_t) \\
f_1^{self,t} &= \left\{ \sum_{i=H^0,h} \eta_i[m_t(-B_0 + Z_i^v + \delta m_i)](\hat{t}, m_t, m_i) \right. \\
&\quad \sum_{i=A,Z} \eta_i[m_t(B_0 + Z_i^v + \delta m_i)](\hat{t}, m_t, m_i) \\
&\quad \left. \sum_{i=H^+,W^+} \eta_i[m_t(Z_i^v + \delta m_i)](\hat{t}, m_b, m_i) \right\} / (\hat{t} - m_t^2)
\end{aligned}
$$

$$
\begin{aligned}
f_2^{self,t} &= \left\{ \sum_{i=H^0,h} \eta_i [B_1 - Z_i^v](\hat{t}, m_t, m_i) \right. \\
&\quad \sum_{i=A,Z} \eta_i [B_1 - Z_i^v](\hat{t}, m_t, m_i) \\
&\quad \left. \sum_{i=H^+,W^+} \eta_i [B_1 - Z_i^v](\hat{t}, m_b, m_i) \right\} / (\hat{t} - m_t^2) \\
f_1^{v1,t} &= -\sum_{i=H^0,h} \eta_i [\frac{1}{2} - 2C_{24} - Z_i^v - m_t^2(2C_{11} + C_{21}) \\
&\quad +2p_2 \cdot p_4(C_{12} + C_{23})](-p_2, p_4, m_i, m_t, m_t) \\
&\quad -\sum_{i=A,Z} \eta_i [\frac{1}{2} - 2C_{24} - Z_i^v - m_t^2(2C_{11} + C_{21}) \\
&\quad +2p_2 \cdot p_4(C_{12} + C_{23})](-p_2, p_4, m_i, m_t, m_t) \\
&\quad -\sum_{i=H^+,W^+} \eta_i [\frac{1}{2} - 2C_{24} - Z_i^v - m_t^2(2C_{11} + C_{21} + C_0) \\
&\quad +2p_2 \cdot p_4(C_{12} + C_{23})](-p_2, p_4, m_i, m_b, m_b) \\
f_2^{v1,t} &= -\sum_{i=H^0,h} \eta_i [2m_t(3C_{11} + C_{21} + 2C_0)](-p_2, p_4, m_i, m_t, m_t) \\
&\quad -\sum_{i=A,Z} \eta_i [2m_t(C_{11} + C_{21})](-p_2, p_4, m_i, m_t, m_t) \\
&\quad -\sum_{i=H^+,W^+} \eta_i [2m_t(2C_{11} + C_{21} + C_0)](-p_2, p_4, m_i, m_b, m_b) \\
f_4^{v1,t} &= \sum_{i=H^0,h} \eta_i [m_t(2C_0 + C_{11})](-p_2, p_4, m_i, m_t, m_t) \\
&\quad \sum_{i=A,Z} \eta_i [m_t C_{11}](-p_2, p_4, m_i, m_t, m_t) \\
&\quad \sum_{i=H^+,W^+} \eta_i [m_t(C_{11} + C_0)](-p_2, p_4, m_i, m_b, m_b) \\
f_5^{v1,t} &= \sum_{i=H^0,h} \eta_i [2(C_{12} + C_{23})](-p_2, p_4, m_i, m_t, m_t) \\
&\quad \sum_{i=A,Z} \eta_i [2(C_{12} + C_{23})](-p_2, p_4, m_i, m_t, m_t) \\
&\quad \sum_{i=H^+,W^+} \eta_i [2(C_{12} + C_{23})](-p_2, p_4, m_i, m_b, m_b) \\
f_1^{v2,t} &= -\sum_{i=H^0,h} \eta_i [\frac{1}{2} - 2C_{24} - Z_i^v - m_t^2(2C_{11} + C_{21}) \\
&\quad +2p_1 \cdot p_3(C_{12} + C_{23})](p_1, -p_3, m_i, m_t, m_t)
\end{aligned}
$$

$$
\begin{aligned}
& - \sum_{i=A,Z} \eta_i[\frac{1}{2} - 2C_{24} - Z_i^v - m_t^2(2C_{11} + C_{21}) \\
& +2p_1 \cdot p_3(C_{12} + C_{23})](p_1, -p_3, m_i, m_t, m_t) \\
& - \sum_{i=H^+,W^+} \eta_i[\frac{1}{2} - 2C_{24} - Z_i^v - m_t^2(2C_{11} + C_{21} + C_0) \\
& +2p_1 \cdot p_3(C_{12} + C_{23})](p_1, -p_3, m_i, m_b, m_b)
\end{aligned}
$$

$$
\begin{aligned}
f_2^{v2,t} &= \sum_{i=H^0,h} \eta_i[2m_t(3C_{11} + C_{21} + 2C_0)](p_1, -p_3, m_i, m_t, m_t) \\
& \sum_{i=A,Z} \eta_i[2m_t(C_{11} + C_{21})](p_1, -p_3, m_i, m_t, m_t) \\
& \sum_{i=H^+,W^+} \eta_i[2m_t(2C_{11} + C_{21} + C_0)](p_1, -p_3, m_i, m_b, m_b) \\
f_4^{v2,t} &= - \sum_{i=H^0,h} \eta_i[m_t(2C_0 + C_{11})](p_1, -p_3, m_i, m_t, m_t) \\
& - \sum_{i=A,Z} \eta_i[m_t C_{11}](p_1, -p_3, m_i, m_t, m_t) \\
& - \sum_{i=H^+,W^+} \eta_i[m_t(C_{11} + C_0)](p_1, -p_3, m_i, m_b, m_b) \\
f_5^{v2,t} &= \sum_{i=H^0,h} \eta_i[2(C_{12} + C_{23})](p_1, -p_3, m_i, m_t, m_t) \\
& \sum_{i=A,Z} \eta_i[2(C_{12} + C_{23})](p_1, -p_3, m_i, m_t, m_t) \\
& \sum_{i=H^+,W^+} \eta_i[2(C_{12} + C_{23})](p_1, -p_3, m_i, m_b, m_b)
\end{aligned}
$$

$$
\begin{aligned}
f_1^{b,t} &= - \sum_{i=H^0,h} \eta_i[f_1^{q2q3} + 4m_t D_{27}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=A,Z} \eta_i[f_1^{q2q3}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=H^+,W^+} \eta_i[f_1^{q2q3} + 2m_t D_{27}](-p_2, p_4, p_3, m_i, m_b, m_b, m_b) \\
f_2^{b,t} &= - \sum_{i=H^0,h} \eta_i[f_2^{q2q3} + 3m_t(-m_t^2 D_{21} + 2p_2 \cdot p_4 D_{24} \\
& +2p_2 \cdot p_3 D_{25} - 2p_3 \cdot p_4 D_{26}) - 8m_t D_{27} \\
& +4m_t(-m_t^2 D_{11} + p_2 \cdot p_4(D_{11} + D_{12} - D_{13}))](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=A,Z} \eta_i[f_2^{q2q3} + m_t(-m_t^2 D_{21} + 2p_2 \cdot p_4 D_{24} \\
& +2p_2 \cdot p_3 D_{25} - 2p_3 \cdot p_4 D_{26}) - 4m_t D_{27}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t)
\end{aligned}
$$

$$
\begin{aligned}
& -\sum_{i=H^+,W^+}\eta_i[f_2^{q2q3}+2m_t(-m_t^2D_{21}+2p_2\cdot p_4D_{24} \\
& +2p_2\cdot p_3D_{25}-2p_3\cdot p_4D_{26})-6m_tD_{27}+m_t(-3m_t^2D_{11} \\
& +2p_2\cdot p_4(D_{11}+D_{12}-D_{13}))-m_t^3D_0](-p_2,p_4,p_3,m_i,m_b,m_b,m_b) \\
f_3^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_3^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=A,Z}\eta_i[f_3^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=H^+,W^+}\eta_i[f_3^{q2q3}+2m_t^2(D_{12}-D_{13})](-p_2,p_4,p_3,m_i,m_b,m_b,m_b) \\
f_4^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_4^{q2q3}-8m_t^2D_{13}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=A,Z}\eta_i[f_4^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=H^+,W^+}\eta_i[f_4^{q2q3}-2m_t^2D_{13}](-p_2,p_4,p_3,m_i,m_b,m_b,m_b) \\
f_5^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_5^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=A,Z}\eta_i[f_5^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=H^+,W^+}\eta_i[f_5^{q2q3}+2m_t^2(D_{12}-D_{11})](-p_2,p_4,p_3,m_i,m_b,m_b,m_b) \\
f_6^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_6^{q2q3}+8m_t^2(D_0+D_{11}-D_{13})](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=A,Z}\eta_i[f_6^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=H^+,W^+}\eta_i[f_6^{q2q3}+2m_t^2(D_0+2D_{11}-2D_{13})](-p_2,p_4,p_3,m_i,m_b,m_b,m_b) \\
f_7^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_7^{q2q3}+8m_tD_{26}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=A,Z}\eta_i[f_7^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=H^+,W^+}\eta_i[f_7^{q2q3}+4m_tD_{26}](-p_2,p_4,p_3,m_i,m_b,m_b,m_b) \\
f_8^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_8^{q2q3}+8m_t(D_{26}-D_{25})](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=A,Z}\eta_i[f_8^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t) \\
& -\sum_{i=H^+,W^+}\eta_i[f_8^{q2q3}+4m_t(D_{26}-D_{25})](-p_2,p_4,p_3,m_i,m_b,m_b,m_b)
\end{aligned}
$$

$$
\begin{aligned}
f_9^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_9^{q2q3}+8m_t(D_{26}-D_{24}-D_{12})](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=A,Z}\eta_i[f_9^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=H^+,W^+}\eta_i[f_9^{q2q3}+4m_t(D_{26}-D_{24}-D_{12})](-p_2,p_4,p_3,m_i,m_b,m_b,m_b)\\
f_{10}^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_{10}^{q2q3}+8m_t(D_{21}+D_{26}\\
&-D_{24}-D_{25}+D_{11}-D_{12})](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=A,Z}\eta_i[f_{10}^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=H^+,W^+}\eta_i[f_{10}^{q2q3}+4m_t(D_{21}+D_{26}\\
&-D_{24}-D_{25}+D_{11}-D_{12})](-p_2,p_4,p_3,m_i,m_b,m_b,m_b)\\
f_{11}^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_{11}^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=A,Z}\eta_i[f_{11}^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=H^+,W^+}\eta_i[f_{11}^{q2q3}](-p_2,p_4,p_3,m_i,m_b,m_b,m_b)\\
f_{12}^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_{12}^{q2q3}+4m_t^2D_0](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=A,Z}\eta_i[f_{12}^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=H^+,W^+}\eta_i[f_{12}^{q2q3}+m_t^2(D_0+D_{12}-D_{13})](-p_2,p_4,p_3,m_i,m_b,m_b,m_b)\\
f_{13}^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_{13}^{q2q3}-4m_tD_{12}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=A,Z}\eta_i[f_{13}^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=H^+,W^+}\eta_i[f_{13}^{q2q3}-2m_tD_{12}](-p_2,p_4,p_3,m_i,m_b,m_b,m_b)\\
f_{14}^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_{14}^{q2q3}+4m_tD_{13}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=A,Z}\eta_i[f_{14}^{q2q3}](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)\\
&-\sum_{i=H^+,W^+}\eta_i[f_{14}^{q2q3}+2m_tD_{13}](-p_2,p_4,p_3,m_i,m_b,m_b,m_b)\\
f_{15}^{b,t} &= -\sum_{i=H^0,h}\eta_i[f_{15}^{q2q3}+4m_t(D_{11}-D_{12})](-p_2,p_4,p_3,m_i,m_t,m_t,m_t)
\end{aligned}
$$

$$
\begin{aligned}
& - \sum_{i=A,Z} \eta_i[f_{15}^{q2q3}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=H^+,W^+} \eta_i[f_{15}^{q2q3} + 2m_t(D_{11} - D_{12})](-p_2, p_4, p_3, m_i, m_b, m_b, m_b) \\
f_{16}^{b,t} = & - \sum_{i=H^0,h} \eta_i[f_{16}^{q2q3} + 4m_t(D_{13} - D_{11})](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=A,Z} \eta_i[f_{16}^{q2q3}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=H^+,W^+} \eta_i[f_{16}^{q2q3} + 2m_t(D_{13} - D_{11})](-p_2, p_4, p_3, m_i, m_b, m_b, m_b) \\
f_{17}^{b,t} = & - \sum_{i=H^0,h} \eta_i[f_{17}^{q2q3}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=A,Z} \eta_i[f_{17}^{q2q3}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=H^+,W^+} \eta_i[f_{17}^{q2q3}](-p_2, p_4, p_3, m_i, m_b, m_b, m_b) \\
f_{18}^{b,t} = & - \sum_{i=H^0,h} \eta_i[f_{18}^{q2q3}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=A,Z} \eta_i[f_{18}^{q2q3}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=H^+,W^+} \eta_i[f_{18}^{q2q3}](-p_2, p_4, p_3, m_i, m_b, m_b, m_b) \\
f_{19}^{b,t} = & - \sum_{i=H^0,h} \eta_i[f_{19}^{q2q3}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=A,Z} \eta_i[f_{19}^{q2q3}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=H^+,W^+} \eta_i[f_{19}^{q2q3}](-p_2, p_4, p_3, m_i, m_b, m_b, m_b) \\
f_{20}^{b,t} = & - \sum_{i=H^0,h} \eta_i[f_{20}^{q2q3}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=A,Z} \eta_i[f_{20}^{q2q3}](-p_2, p_4, p_3, m_i, m_t, m_t, m_t) \\
& - \sum_{i=H^+,W^+} \eta_i[f_{20}^{q2q3}](-p_2, p_4, p_3, m_i, m_b, m_b, m_b)
\end{aligned}
$$

$$
\begin{aligned}
f_1^{q2q3} &= 2m_t D_{311} \\
f_2^{q2q3} &= -m_t^3 D_{31} + 2m_t(p_2 \cdot p_4 D_{34} + p_2 \cdot p_3 D_{35} - p_3 \cdot p_4 D_{310} - 2D_{311}) \\
& \quad -m_t^3 D_{21} + 2m_t[p_2 \cdot p_4(D_{21} - D_{25}) - p_2 \cdot p_3 D_{25} + p_3 \cdot p_4 D_{26} + D_{27}]
\end{aligned}
$$

$$
\begin{aligned}
f_3^{q2q3} &= 2[m_t^2(D_{34}-D_{35})+2p_2\cdot p_3(D_{37}-D_{310})+2p_3\cdot p_4(D_{38}-D_{39}) \\
&\quad +2p_2\cdot p_4(D_{310}-D_{36})+4D_{312}-6D_{313}] \\
&\quad +4m_t^2(D_{24}-D_{25})+4p_2\cdot p_4(D_{25}+D_{26}-D_{22}-D_{23})+4D_{27} \\
f_4^{q2q3} &= 2[m_t^2D_{35}-2p_2\cdot p_3D_{37}+2p_3\cdot p_4D_{39}-2p_2\cdot p_4D_{310}+4D_{313}] \\
&\quad +4p_2\cdot p_4(D_{23}-D_{25}) \\
f_5^{q2q3} &= 2[m_t^2(D_{34}-D_{31})+2p_2\cdot p_4(D_{34}-D_{36})+2p_2\cdot p_3(D_{35}-D_{310}) \\
&\quad +2p_3\cdot p_4(D_{38}-D_{310})-4D_{311}+4D_{312}] \\
&\quad +4m_t^2(D_{24}-D_{21})+4p_2\cdot p_4(D_{24}-D_{22}) \\
f_6^{q2q3} &= 4(D_{311}-D_{313})+2m_t^2(D_{21}-2D_{25})+4p_2\cdot p_3D_{25}+4p_2\cdot p_4D_{26}-4p_3\cdot p_4D_{26} \\
f_7^{q2q3} &= 4m_tD_{310} \\
f_8^{q2q3} &= 4m_t(D_{310}-D_{35}) \\
f_9^{q2q3} &= 4m_t(D_{310}-D_{34})-4m_tD_{24} \\
f_{10}^{q2q3} &= 4m_t(D_{31}-D_{34}-D_{35}+D_{310})+4m_t(D_{21}-D_{24}) \\
f_{11}^{q2q3} &= 2(D_{313}-D_{312})-2D_{27} \\
f_{12}^{q2q3} &= m_t^2(D_{34}-D_{35})+2[p_2\cdot p_4(D_{310}-D_{36})+p_2\cdot p_3(D_{37}-D_{310}) \\
&\quad +p_3\cdot p_4(D_{38}-D_{39})+2D_{312}-2D_{313}] \\
&\quad +m_t^2(2D_{24}-2D_{25}-D_{21}) \\
&\quad +2[p_2\cdot p_4(D_{25}+2D_{26}-D_{22}-D_{23})+p_2\cdot p_3D_{25}-p_3\cdot p_4D_{26}] \\
f_{13}^{q2q3} &= -2m_tD_{24} \\
f_{14}^{q2q3} &= 2m_tD_{25} \\
f_{15}^{q2q3} &= 2m_t(D_{21}-D_{24}) \\
f_{16}^{q2q3} &= 2m_t(D_{25}-D_{21})
\end{aligned}
$$

$$
\begin{aligned}
f_{17}^{q2q3} &= 4(D_{39}-D_{38})+4(D_{23}-D_{26}) \\
f_{18}^{q2q3} &= 4(D_{39}+D_{310}-D_{37}-D_{38})+4(D_{25}-D_{26}) \\
f_{19}^{q2q3} &= 4(D_{36}+D_{39}-D_{38}-D_{310})+4(D_{22}+D_{23}-D_{25}-D_{26}) \\
f_{20}^{q2q3} &= 4(D_{35}+D_{36}-D_{34}-D_{37}-D_{38}+D_{39})+4(D_{22}-D_{24}+D_{25}-D_{26}).
\end{aligned}
$$

In the above formulae

$$
\begin{aligned}
&k = p_1+p_2 = p_3+p_4, \;\; \hat{s}=k^2, \;\; \hat{t}=(p_2-p_4)^2, \;\; \hat{u}=(p_2-p_3)^2, \\
&\Gamma^\mu = (-p_4+p_3)^\mu \epsilon(p_3)\cdot\epsilon(p_4) + (2p_4+p_3)\cdot\epsilon(p_3)\epsilon(p_4)^\mu - (2p_3+p_4)\cdot\epsilon(p_4)\epsilon(p_3)^\mu, \\
&\eta_{H^0} = \frac{\sin^2\alpha}{\sin^2\beta}, \;\; \eta_{H^0} = \frac{\cos^2\alpha}{\sin^2\beta}, \\
&\eta_A = \cot^2\beta, \;\; \eta_{H^+} = (\cot^2\beta + \frac{m_b^2}{m_t^2}\tan^2\beta), \;\; \eta_Z = \eta_{W^+} = 1.
\end{aligned}
$$

The renormalization constants are:

$$
\begin{aligned}
Z_i^v &= [B_1 + 2m_t^2(G_0+G_1)](m_t^2, m_t, m_i) \;\; for \;\; i = H^0, \; h \\
Z_i^v &= [B_1 + 2m_t^2(G_1-G_0)](m_t^2, m_t, m_i) \;\; for \;\; i = A, \; Z \\
Z_i^v &= [B_1 + 2m_t^2 G_1](m_t^2, m_b, m_i) \;\; for \;\; i = H^+, \; W^+
\end{aligned}
$$

$$
\begin{aligned}
\delta m_i &= [B_0 - B_1](m_t^2, m_t, m_i) \;\; for \;\; i = H^0, \; h \\
\delta m_i &= [-B_0 - B_1](m_t^2, m_t, m_i) \;\; for \;\; i = A, \; Z \\
\delta m_i &= [-B_1](m_t^2, m_b, m_i) \;\; for \;\; i = H^+, \; W^+
\end{aligned}
$$

where $G_0 = -\frac{dB_0(p^2,m_1,m_2)}{dp^2}|_{p^2=m_t^2}$, $G_1 = \frac{dB_1(p^2,m_1,m_2)}{dp^2}|_{p^2=m_t^2}$ .

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# Figure Captions

Fig.1 Feynaman diagrams of tree level and $O(\alpha m_t^2/m_W^2)$ Yukawa corrections of $gg \to t\bar{t}$.

Fig.2 Results of Yukawa corrections in the Standard Model.

Fig.3 Results of Yukawa corrections in the general Two-Higgs-Doublet Model with $\beta = 0.25$.

Fig.4 Results of Yukawa corrections in the Minimal Supersymmetric Standard Model with $\beta = 0.25$.

Fig.5 Results of Yukawa corrections in the Minimal Supersymmetric Standard Model with $\beta = \pi/4$.

Fig.6 Results of Yukawa corrections in the Minimal Supersymmetric Standard Model with $\tan\beta = 70$.